Flow dynamics in mid-Jurassic dikes and sills of the Ferrar large igneous province and implications for long-distance magma transport

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Abstract

Magma flow paths in sill-fed dikes of south Victoria Land, Ferrar large igneous province (LIP), contrast with those predicted by classic models of dike transport in LIPs and magmatic rift settings. We examine anisotropy of magnetic susceptibility (AMS) flow paths in dike networks at Terra Cotta Mountain and Mt Gran, which intruded at paleodepths of ~2.5 and ~1.5 km. These intrusions (up to 30 m thick) exhibit irregular, interconnected dike-sill geometries and adjoin larger sills (~200-300 m thick) at different stratigraphic levels. Both shallowly dipping and sub-vertical magma flow components are interpreted from AMS measurements across individual intrusions, and often match macroscopic flow indicators and variations in dike attitudes. Flow paths suggest that intrusive patterns and magma flow directions depended on varying stress concentrations and rotations during dike and sill propagation, whereas a regional extensional tectonic control was negligible or absent. Unlike giant dike swarms in LIPs elsewhere (e.g., 1270 Ma MacKenzie LIP), dikes of the Ferrar LIP show no regionally consistent vertical or lateral flow patterns, suggesting these intrusion where not responsible for long-distance transport in the province. In the absence of regionally significant, colinear dike swarms, or observed intrusions at crustal depths ≥4 km, we suggest that long distance magma transport occurred in sills within Beacon Supergroup sedimentary rocks. This interpretation is consistent with existing geochemical data and thermal constraints, which support lateral magma flow for ~3,500 km across the Gondwana supercontinent before freezing.

Keywords

Antarctica; anisotropy of magnetic susceptibility; thermo-mechanical model; sill-fed dikes; Terra Cotta Mountain; Mount Gran

1. Introduction

Investigating how magma is transported and accommodated in the crust can yield key insights into the processes governing the growth and breakup of continental lithosphere (Buck, 2004; Ebinger et al., 2013), and the dynamics of magmatic systems that feed volcanic eruptions (Tibaldi, 2015). In large igneous provinces (LIPs), the intrusive components controlling both the lateral and vertical migration of magma transport are often depicted as colinear swarms of giant dikes (Ernst et al., 1995; Ernst et al., 2001). The primary direction of magma flow documented for these dike systems changes from vertical near the plume head (300-500 km from plume center) to lateral away from the source. Examples include the 1270 Ma MacKenzie and ~180 Ma Okavango dike swarms (Ernst and Baragar, 1992; Aubourg et al., 2008). However, the shallow plumbing systems (<10 km depth) of a few LIPs, such as the 250 Ma Siberian LIP, form interconnected sill networks capable of feeding voluminous outpourings of lavas (Naldrett et al., 1995; Cartwright and Hansen, 2006; Muirhead et al., 2014). The geometries of dikes within these sill-dominated provinces differ from classic depictions of LIP dike systems. These intrusions, termed by Muirhead et al. (2014) as sill-fed dikes (but also referred to previously as inclined “sheets”; Airoldi et al., 2011), exhibit short lengths (<5 km), variable dips (10-90°), form at sill peripheries, and link sills at different stratigraphic levels (Johnson and Pollard, 1973; Czamanske et al., 1995; Muirhead et al., 2012).

Although sill-fed dikes form a key component of the shallow plumbing systems of sill-dominated LIPs, magma flow dynamics within these intrusions remain largely unknown. Many studies focus on magma transport through the outer sheets and internal sills of saucer-shaped intrusions (Ferré et al., 2002; Thomson and Hutton, 2004; Hansen and Cartwright, 2006a; Maes et al., 2008; Polteau et al., 2008b; Galland et al., 2009). In the Karoo LIP arrangement of intrusive segment ‘lobes’ and flow kinematics from anisotropy of magnetic susceptibility (AMS) suggest an up-dip flow component in the outer inclined sheets that connect to sill peripheries (Polteau et al., 2008a; Schofield et al., 2010; Galerne et al., 2011). Airoldi et al. (2012), however, revealed complex lateral and vertical magma flow patterns in shallowly dipping, sill-fed dikes in the Allan Hills region of Ferrar LIP, Antarctica. These data were interpreted to record intermittent phases of 'passive' magma injection into fracture networks forming in response to the forceful injection of underlying sills. However, it is currently unknown whether this model of dike growth is regionally consistent throughout the Ferrar LIP. The role that dikes played in controlling the regional distribution of Ferrar magmas is therefore poorly constrained.

We analyze magma transport dynamics at various depths in the magmatic plumbing system of the Ferrar LIP. Emplaced ~10 million years prior to the breakup of East from West Gondwana, this widespread (c.a. 4,100 km long) magmatic province forms part of the ~183 Ma Karoo-Ferrar LIP (Encarnaciòn et al., 1996), and provides important insights into the tectono-magmatic conditions across Antarctica during this continental breakup event. AMS is applied to Ferrar intrusions at Terra Cotta Mountain and at Mt Gran, south Victoria Land (Fig. 1), to constrain a model for magma transport dynamics throughout the province. These analyses are used to infer (1) controls on intrusion propagation at different levels of the plumbing system, (2) characteristic flow modes within dikes and sills, and (3) the intrusive structures responsible for broad-scale magma transport throughout the Ferrar LIP.

2. The Ferrar large igneous province

Ferrar LIP rocks are exposed for 3,500 km along the Transantarctic Mountains of East Antarctica. These intrusive and extrusive rocks, with a total estimated volume around 300,000 km^3 (Ross et al., 2005), represent the most laterally extensive LIP system on Earth. Studies addressing the broad-scale emplacement of the province support a lateral transport model, with Ferrar magmas travelling >3,000 km from the Weddell Sea across the east Antarctic margin into south-eastern Australasia (Elliot et al., 1999; Elliot and Fleming, 2000; Leat, 2008). Emplacement of the province occurred over 349 ±49 kyr (Burgess et al., 2015), during (or just prior to) the earliest stages of Gondwanaland breakup, and coincided with the emplacement of the earliest Karoo lavas and sills (U-Pb ages on zircon and baddeleyite between 183.6 ± 1.0 and 182.8 Ma, cf. Encarnaciòn et al., 1996 and Burgess et al., 2015, and references therein). The cross-continental distribution of Ferrar LIP rocks has led authors to suggest that Ferrar magmas intruded and erupted in a continental rift system driven by regional extension, or trans-tension, in a back-arc setting (Wilson, 1993; Storey, 1995; Elliot, 2013). However, intrusion and fracture systems trends consistent with regional extension in the Jurassic are lacking (Muirhead et al., 2012). Instead, regional dike patterns are consistent with magma emplacement under a far-field neutral stress regime (Muirhead et al., 2014).

Ferrar intrusions are observed dissecting the flat-lying, ~2.5 km-thick Beacon Supergroup sedimentary sequence and the upper ~0.5 km of underlying basement granitoid, amphibolite and metasedimentary rocks (Elliot and Fleming, 2008). Sills are significantly more voluminous than dikes (Muirhead et al., 2014). In south Victoria Land, sills reach ~5,000 km2 in area and up to 450 m in thickness (Gunn and Warren, 1962). Some sills are observed ascending the stratigraphy in a 'step-wise' fashion (Elliot and Fleming, 2004; Airoldi et al., 2011) and, within the upper Permian and lower Triassic members of the Beacon sequence, sills become progressively thinner (0-100 m) in places and laterally less continuous (Elliot and Fleming, 2004, 2008).

Swarms of shallow to moderately dipping dike intrusions are reported from various localities in the central Transantarctic Mountains (e.g. Hornig, 1993; Leat, 2008 and references therein) and south Victoria Land (Skinner and Ricker, 1968; Wilson, 1993; Morrison and Reay, 1995; Muirhead et al., 2014). Regional field and remote sensing studies reveal that these intrusions connect sills at different stratigraphic levels, and are inferred to assist in the vertical transport of magma in the upper 4 km of the plumbing system to the surface (Muirhead et al., 2012; Muirhead et al., 2014). Magma flow dynamics within these sill-fed dikes are, however, poorly constrained.

3. Field sites

3.1. Terra Cotta Mountain

Dike intrusions in the Terra Cotta Mountain area are exposed along NE- and SW-facing cliffs (Fig. 2 in Morrison and Reay, 1995). These cliffs reveal a swarm of moderately dipping (mean dip 51°: Muirhead et al., 2012) intrusions dissecting Beacon Supergroup rocks and connecting to the lower contact of a sill capping the mountain (Muirhead et al., 2012). Mt Kuipers lies immediately east of Terra Cotta Mountain, where a ~200 m-thick sill and two dike intrusions can be seen on the western flanks. Basement granitoids exposed at the northern foothill of the nunatak underlie a sequence of quartz-rich sandstones, siltstones and minor mudstones and conglomerates. These sedimentary sequences belong to units from the Windy Gully Sandstone to the Beacon Heights Orthoquartzite of the ~1.5 km thick Taylor Group rocks (Harrington, 1958; Gunn and Warren, 1962; Ross et al., 2008). A ~1.0 km-thick sequence of relatively undeformed, flat-lying, sedimentary rocks of the Victoria Group lie unconformably on Taylor Group rocks. At Terra Cotta Mountain, Ferrar intrusions are observed dissecting rocks of the Windy Gully Sandstone up to the Arena Sandstone, which suggests emplacement at paleodepths of ~1.5 – 2.5 km (cf. Fig. 1) (Morrison, 1989; Muirhead et al., 2012).

Dike attitudes at Terra Cotta Mountain are irregular, with orientations varying along strike to form zig-zag patterns. Intrusion dips also vary up-section, where some intrusions change into sills that connect offset dike segments, resulting in a transgressive dike geometry (Airoldi et al., 2011). Some intrusions bifurcate locally into smaller dikes. For example, dikes up to 10 m thick can be seen connecting to smaller (2-6 m thick), 'offshoot' dikes, some of which in turn feed into thinner (<2 m thick) ones (Fig. 2a). Offshoot dikes are characterized by irregular geometries, with different segments exhibiting left- and right-steps, both along-strike and up-section, and curved tips (Fig. 2b).

The relative timing of diking events is ambiguous on the SE slopes of Terra Cotta Mountain. Although dikes do cross one another in places, no chilled margins are observed along intrusive contacts that would allow interpretation of the relative timing of intrusion events. However, within individual dikes, chilled contacts are observed trending sub-parallel to the plane of the intrusion (Fig. 3a-c). Chilled zones within intrusions exhibit either sharp or diffuse contacts. Thin zones comprising a mixture of un-melted, baked and thermo-mechanically deformed host rock material, host rock fragments, calcite veins, and chilled dolerite fragments are observed within some dikes, and trend sub-parallel to the nearest intrusion margin. Similar contact relationships also appear along dike selvages (Fig. 3b-c).

'Baked' zones are common in the host rock alongside intrusion margins and are typically 1-2 cm wide. Evidence of thermo-mechanical deformation affecting both country rock and dolerite is observed at several locations. For example, where sharp selvages are present, country rock at the margins of intrusions exhibits deformed surfaces (Fig. 4). Striations and, locally, discontinuous veins 1-10 cm wide, are also observed on country rock walls, along dike margins. These locally exhibit mineral striations with near-vertical lineations (Fig. 4a). No fault planes dissecting the dikes were observed. Variably shaped cusps-and-grooves and drag folds are preserved along country rock margins (Fig. 4b and c). There are peperite zones in sedimentary rocks near some intrusion margins. These zones include chaotic arrays of angular fragments and/or rounded pods of chilled dolerite, intermingled with lithified medium-to-fine sand material (Fig. 3d).

3.1.1. Target intrusions

The principal intrusions investigated in this study are shown in Fig. 5. At the base of Terra Cotta Mountain is a >20 m-thick intrusion (d#3). The lower contact of the intrusion is visible, striking 340° and dipping east at 75°. However, the upper contact cannot be seen anywhere in the field area, and the intrusion does not appear to have significant lateral continuity. Near the summit of the mountain, multiple intrusions are observed branching out from d#3 upwards, into the thick (>100 m) sill that caps the mountain (s#4). On the northern and eastern slopes of the mountain variably dipping (2-76°) intrusions exhibit alternating dike-sill geometries (e.g., t#1a-b, and t#2). On the western slopes of Mt Kuipers is a ~200 m-thick sill, a ~20 m-thick, ~090° striking dike (d#5), and a 10 m-thick, ~160° trending dike (d#6). The latter dike (d#6) tapers down and ends to the north-west before reaching d#5, and it was not observed on Terra Cotta Mountain's southeastern cliff. Further south-east on Mt Kuipers, d#6 truncates the sill.

3.2. Mount Gran

Mt Gran is located ~30 km south-east of Allan-Coombs Hills. Here, a steep, ~750 m high, southeast-facing cliff exposes a complex network of intrusions (White et al., 2009) (Fig. 5e). These Ferrar dikes and sills intrude upper Taylor Group and lower Victoria Group rocks. Based on thickness estimates for the Taylor Group (Harrington, 1958; Gunn and Warren, 1962), we infer that Ferrar intrusions at Mt Gran were emplaced at a paleodepth of 1-1.5 km (White et al., 2009; Fig. 1). The most prominent intrusion at Mt Gran is a ~30 m-thick, sub-vertical dike (d#7), which truncates a >40 m-thick sill (s#8). A network of interconnected sills and transgressive dikes, all less than 20 m thick (s#9), are exposed on the northeastern side of the cliff. These shallowly dipping (typically <30°) intrusions transgress the stratigraphy up-section to the southwest, before merging into d#7 (Fig. 5e). Other inclined intrusions also extend outward from the western margin of d#7. Two dikes (d#10 and d#11) are exposed in a valley a few hundred metres northwest of the cliff, and exhibit 086° and 056° strikes.

4. Methods: anisotropy of magnetic susceptibility

Paleo-magma flow directions can be determined by analyzing the preferred alignments and orientations of Fe-bearing minerals using a method known as anisotropy of susceptibility (AMS) (Tarling and Hrouda, 1993). This non-destructive approach has become common in the last few decades due to its time- and cost-effectiveness, and is commonly used to constrain interpretations of dike and sill emplacement dynamics within volcanic plumbing systems (see Baer and Reches, 1987; Walker et al., 1999; Ferré et al., 2002; Liss et al., 2002; Poland et al., 2004; Delcamp et al., 2014 for a few examples) from the 'primary', dominant magmatic flow indicated by AMS fabrics (e.g., Hrouda, 1982; Dragoni et al., 1997; Stevenson et al., 2007; Magee et al., 2012b). This method has also been used to understand the broad scale emplacement of LIPs, such as the MacKenzie LIP (Ernst and Baragar, 1992), the volcanic margin of east Greenland (Callot and Geoffroy, 2004), the Karoo LIP (Aubourg et al., 2008; Polteau et al., 2008b), the British and Irish Paleogene igneous province (Magee et al., 2012a), and the Siberian LIP (Callot et al., 2004).

4.1. Sampling and analyses

Data presented in this study come from 97 oriented block samples collected close to the walls of Ferrar dikes and sills at Terra Cotta Mountain (81 samples) and Mt Gran (16 samples). The orientations of dolerite block samples were determined in the field with both solar and magnetic compasses and a clinometer. Samples sizes were approximately 10×10×15 cm, to provide sufficient material to perform petrographic and magnetic analyses. Depending on intrusion size and outcrop accessibility, sampling was also performed across intrusion interiors in order to detect any significant compositional and/or textural variations. Where possible, both walls of intrusions were sampled to investigate imbricated magnetic foliations (Knight and Walker, 1988).

Samples were prepared for petrographic and magnetic analysis at the University of Otago Geology Department and Otago Paleomagnetic Research Facility (OPRF), New Zealand. At least one sample per intrusion was petrographically analyzed. Between 3 and 15 core specimens (diameter = 25 mm, length = 22 mm) were taken from every block sample for magnetic analyses. Magnetic susceptibility and AMS measurements on over 500 core specimens from Terra Cotta Mountain were analyzed at the inter-university research centre Alpine Laboratory of Paleomagnetism (ALP - Peveragno, Italy), using an AGICO KLY-3 Kappabridge. Susceptibility versus temperature analyses were run for one selected specimen per intrusion using a CS-3 furnace at OPRF. Isothermal remanent magnetization (IRM) acquisition, thermal demagnetization and backfield curves were obtained either using a JR-6 spinner magnetometer (Lowrie, 1990) at ALP, or with a Princeton Instruments Vibrating Sample Magnetometer at OPRF. Magnetic carriers in igneous rocks from Terra Cotta Mountain were determined through the analysis of rock magnetic properties. This included magnetic susceptibility, defined by the ratio between the induced magnetization of the material and the inducing magnetic field, IRM, remanence coercivity (B_{CR}), temperature-dependant susceptibility (K_T *vs* T), blocking (T_B), and Curie temperatures (T_C) at which magnetic minerals lost their magnetic properties.

AMS of Mt Gran intrusions was measured using a KLY-4s Kappabridge apparatus at the University of Southern California. Natural remanent magnetization (NRM) and stepwise alternating field (AF) demagnetization measurements were performed with a 2-G cryogenic magnetometer with inline AF demagnetizer (up to 200 mT). T_B spectra and an estimate of Curie temperatures were determined on a ASC thermal demagnetizer. The magnetic mineralogy of Mt Gran samples was determined by combining information such as AMS and NRM, remanence coercivity and Curie and blocking temperatures.

4.2. Interpretation of magnetic fabrics

Flow textures in intrusive rocks are the result of the hydrodynamic alignment of elongate crystals during magma flow. Fe-Ti oxides such as (titano-)magnetite mimic this alignment because they form within and/or along the edges of earlier crystallized, non-ferromagnetic crystals (e.g. feldspar) after magma flow has ceased. As a consequence, flow directions are commonly inferred from the arrangement and orientations of all magnetic components within the rock fabric and overall intrusive body.

The anisotropy of magnetic susceptibility, or AMS, is modelled as an ellipsoid with mutually orthogonal axes $k_1 \geq k_2 \geq k_3$ (respectively, maximum, intermediate and minimum susceptibility axes). These axes can be graphically plotted as lineations on equal area stereographic projections (Fig. 6). The anisotropy parameters defined for any magnetic fabric ellipsoid are the mean magnetic susceptibility (K_m) and anisotropy degree (P or P_J, corrected anisotropy degree) defining the absolute anisotropy of a rock specimen, and magnetic lineation (L), foliation (F), and shape parameter (T) (see Tarling and Hrouda, 1993, table 1.1, p. 18, for their mathematical expression). Together, L, F and T define the geometry of the AMS ellipsoid. Prolate fabric ellipsoids are elongate ($L > F$) and characterized by $-1 \leq T < 0$, whereas oblate ellipsoids are flattened ($F > L$) and characterized by $0 \leq T \leq 1$. In the directional analysis of AMS fabrics, magnetic lineation and foliation correspond respectively to the maximum susceptibility axis direction k_1, and to the plane perpendicular to k_3 and defined by k_1 and k_2 i.e. the magnetic foliation plane (FPL).

Susceptibility and its parameters also depend upon the magnetocrystalline properties and/or distribution of each magnetic mineral species. Ferromagnetic multi-domain (titano-)magnetite grains are the common magnetic carriers in mafic igneous rocks and typically produce a prolate AMS fabric, whose magnetic lineation and foliation are aligned with the plane of the intrusion (or imbricated up to 30°, cf. Dragoni et al., 1997) and indicate the flow direction during magma emplacement (Tarling and Hrouda, 1993). For this type of fabric, also termed a *normal fabric* (N, in Fig. 6), the minimum susceptibility axis is sub-perpendicular to the intrusion plane (IPL).

Magnetic fabrics in intrusive rocks are, however, also known to exhibit deviations from the normal fabric described above. Imbrication angles of 30° to 45°between the FPL and intrusion plane, as well as the exchange of the intermediate and minimum axes of the fabric ellipsoid, are commonly related to composite magnetic mineralogy of AMS sources with different properties (e.g. Ferré, 2002; Aubourg et al., 2008). These are known as *intermediate fabrics* (I_1 – I_3 in Fig. 6), and are classified after Airoldi et al. (2012, and references therein) as 3 types:

- I_1 AMS fabrics are prolate, with the magnetic lineation lying within 45° from the intrusion plane and k_2 and k_3 dispersed on a girdle.
- I_2 fabrics are either prolate or oblate, have both k_1 and k_3 aligned with the intrusion plane and FPL orthogonal to it.

- I_3 is a 'nearly normal' planar fabric, with intrusion and magnetic foliation planes sub-parallel to one another, and imbrication or intersection angle >30°; the intermediate susceptibility k_2, rather than the magnetic lineation k_1, lies closest to the intrusion plane. For fabrics of this type, either k_2, or the intersection between intrusion and magnetic foliation planes, can be used as proxy of the magma flow direction (e.g. Geoffroy et al., 2002).

The last fabric type presented in this study, termed *inverse* (R, in Fig. 6), is related to the presence of single-domain magnetic grains within the rock (Rochette et al., 1999; e.g. Airoldi et al., 2012). This fabric type is characterized by minimum susceptibility axes aligned within the intrusion plane, and the magnetic foliation perpendicular to the intrusion.

4.3. Corroboration of AMS data

AMS fabrics were also compared with macroscopic indicators of magma flow observed in the field. In these instances, the shape, trend and plunge of preserved macroscopic features both within dikes and along intrusion selvages were used to corroborate AMS data. Some studies use the orientation of the long axis of a broken bridge or step structure between dike and sill segments (Airoldi et al., 2012 and references therein) or microscopic alignments of minerals and vesicles as direct indicators of magma flow (e.g. Geshi, 2008; Soriano et al., 2008). Cusps-and-grooves and plumose structures along dike selvages may give information on both the local magma flow lineation and sense of shear along an intrusion (Varga et al., 1998; Correa-Gomes et al., 2001; Baer et al., 2006; Urbani et al., 2015). Striations on dike walls could represent both magma flow, and shear between magma and encasing rocks related to dike opening (e.g. Correa-Gomes et al., 2001; Baer et al., 2006) and/or early-stage shear fracturing ahead of a propagating dike tip (Wilson et al., 2016). In the current study, AMS results were compared with flow directions indicated by the presence of cusps-and-grooves and drag folds observed along 5 intrusions out of 7 at Terra Cotta Mountain (all but d#3 and t#1b). No flow indicators were recorded at Mt Gran.

5. Source of Ferrar Dolerite magnetism

The interpretation of magnetic fabric properties in rocks requires the identification of magnetic carriers. The general petrographic characteristics observed in Terra Cotta Mountain and Mt Gran dolerites are described below, followed by a description of the results of magnetic mineralogy tests and their significance.

5.1. Petrographic characteristics

Ferrar dolerites from the two study locations are compositionally and texturally similar. They exhibit a narrow range of crystal sizes (commonly 100 μm to 500 μm) and compositions. All samples contain a combination of orthopyroxenes, clinopyroxenes and plagioclase, with variable amounts of opaques and secondary/alteration minerals. Larger pyroxene crystals occasionally enclose tabular plagioclase. Rutile and magnetite either included within or between grains are the main opaque phases observed at Terra Cotta Mountain, whereas small amounts of magnetite and hematite with variable Fe-Ti content were determined from reflected light microscopy in Mt Gran intrusions, near or within pyroxene crystals.

At Terra Cotta Mountain, d#3 and d#5 are characterized by the above mineral assemblage, with orthopyroxene enstatite and clinopyroxene augite and pigeonite crystals around 50-60%, and commonly ≤40% plagioclase crystals. Within t#1a-b and t#2, orthopyroxene becomes less common, and clinopyroxene and plagioclase increase in abundance up-section. S#4 and the intrusions at Mt Gran are petrographically similar. In these intrusions, plagioclase is the most abundant mineral phase (40-60%), with 25-40% clinopyroxene (Aug±Pig), and <20% orthopyroxene.

Terra Cotta Mountain dolerite textures are commonly microlitic porphyritic to glomeroporphyritic, with no visible microscopic or macroscopic flow textures (Fig. 7a and b). Glass is uncommon, with the exception of a few chilled margins. Iron oxides and alteration products regularly replace the microlitic groundmass, and are especially common in s#4 and d#6 (Fig. 7b).

At Mt Gran, variations in crystal size, shape, and texture occur as function of proximity to chilled margins. Fine-grained textures with intersertal regions of glassy mesostasis, pervasive opaques and alteration products are commonly observed near intrusion margins (e.g., samples Mg 18-1a and 1-1b). Glomeroporphyritic and/or microlithic porphyritic textures characterize the internal portions of dolerite intrusions (e.g., the center of d#7), where opaques and alteration products also become less abundant (e.g., Mg 14-1a to Mg 17-1a, see supplementary Table S1).

5.2. Magnetic mineralogy properties

Magnetic properties of Terra Cotta Mountain and Mt Gran intrusions are rather uniform. K_m values range from 724 to 62183 µSI and 423 to 40800 µSI, respectively, with ~90% of the data on the orders of 10^{-3} and 10^{-2} SI. The degree of anisotropy is normally 1-5%, with maximum values of 1.047. The least anisotropic samples were collected on d#5.

Thermomagnetic curves obtained from K_T *vs* T tests on Terra Cotta Mountain dolerites present either a stable (two specimens) or, commonly, an irregular behavior, where the curves display upward inflexions of the bulk susceptibility and decay around 400 °C (Fig. 8a). Significant final alteration of the specimens at high temperature is uncommon. For example, there is no sharp variation in susceptibility at the end of the progressive thermal demagnetization (PTD); instead, a gradual removal of the total rock magnetization occurs between 550 and 600 °C. Plots of magnetic intensity upon PTD from Mt Gran samples also show drops in the 550 - 600 °C thermal interval.

Similarly, steep IRM decay occurs as temperatures approach 400 °C during PTD of different B_{CR} fractions (Fig. 8b). This IRM decay is not accompanied by irregular K_m *vs* T paths (Fig. 8d) which, if present, would indicate mineralogical alteration. Soft remanence coercivity (B_{CR} < 500 mT) magnetic components isolated with the Lowrie test are normally over 58%, and the total contributions from the medium (500 < B_{CR} < 1000 mT) and hard magnetic fractions ($B_{CR} \geq$ 1000 mT) are below 37% and 7%, respectively (Fig. 8b).

Saturation of Ferrar specimens is reached with applied field values (B_S) of 300 mT, indicating a dominant low-coercivity magnetic phase. Additional irregular steps observed in the IRM decay curves are likely due to demagnetization of soft and medium B_{CR} fractions (B_{CR} ranging between 30 and 60-70 mT) during application of the back field (Fig. 8c).

5.3. Interpretation of magnetic carriers

Magnetic saturation, remanence coercivity and Curie temperature values determined for Terra Cotta Mountain dolerites, with remanence coercivity overlap in IRM plots, indicate the presence of both soft and medium remanence coercivity magnetite and/or maghemite (cf. Borradaile and Jackson, 2004 and references therein). Magnetite is the common magnetic carrier in basalts (see Tarling and Hrouda, 1993). However, selective oxidation of magnetite can lead to formation of maghemite, particularly in hydrothermal environments (see O'Reilly, 1983; de Boer and Dekkers, 1996). It is possible that magnetite present in Ferrar dolerites altered to maghemite during, for example, a post-Ferrar hydrothermal event in south Victoria Land (e.g. Craw et al., 1992; Ballance and Watters, 2002). In fact, the predominance of K_m values $>10^{-3}$ SI indicates contributions from both ferromagnetic (e.g. (titano-) magnetite and maghemite) and paramagnetic (e.g. pyroxenes and micas) minerals to the magnetic properties of the samples (Owens, 1974; Rochette, 1987; Hrouda, 2002 and references therein).

Uniformity of magnetic properties, with blocking temperatures around 550 °C and low coercivities, suggests magnetite with variable Ti-content is the dominant magnetic carrier in Mt Gran rocks.

We infer a magnetic mineralogy derived from contributions by different magnetic carriers (for instance, accessory magnetic minerals such as pyrrhotite and titanohematite) from petrographic observation of a diffuse oxidation patina in a few samples, occasionally associated with un-differentiated opaque minerals, and magnetic properties. As discussed in Section 5.2, bulk susceptibility inflexion and decay, and steepening of IRM curves around 400 °C during progressive thermal demagnetization of Terra Cotta Mountain samples occur in the absence of any observable mineralogical alteration in the samples. These variations in IRM are, however, consistent with breakdown of pyrrhotite around 300-400°, and may represent reorganization and/or recrystallization of heated magnetic grains in both the single and multi-domain state (Thompson and Oldfield, 1986; Hopkinson, 1989).

6. Anisotropy of magnetic susceptibility of Ferrar intrusions

The presence of magnetite and/or maghemite as main magnetic carrier(s) in Ferrar samples is demonstrated by the magnetic properties, and validates the interpretation of ‘normal’ and ‘intermediate’ magnetic fabrics on the basis of the magnetic lineation direction k_1 and magnetic foliation plane (see also Section 4.2).

6.1. Magnetic fabric distribution

Terra Cotta Mountain samples are characterized by both prolate (55%) and oblate (45%) magnetic susceptibility ellipsoids. AMS fabric types include normal (23%), I-type (59%) and inverse (4%), and 14% of samples exhibit (near-) isotropic magnetic fabrics ($P< 1.005$, $F=L$, low values in tests of anisotropy). Sample-by-sample AMS parameters defined for Terra Cotta Mountain dataset are presented in supplementary Table S2. Similarly at Mt Gran, samples exhibit both prolate (56%) and oblate (44%) magnetic susceptibility ellipsoids. Normal and intermediate AMS fabrics comprise ~20% and ~45% of the total data, respectively. 40% of Mt Gran dataset (s#8, two d#11 sites and three of the eastern sills/shallowly dipping sheets sites) is characterized by anomalous oblate reverse fabrics. Samples producing either isotropic or inverse fabrics (30% of Terra Cotta Mountain samples and ten sites from Mt Gran) were discarded from directional AMS analysis.

6.2. AMS flow directions

Samples from Terra Cotta Mountain and Mt Gran were grouped into 35 and 16 sub-sections, respectively (Tables 1 and 2). Each sub-section contains data analyzed from 1 to 4 sample sites on individual intrusions. Samples within each sub-section produced consistent AMS fabrics and directions.

Maximum and/or intermediate susceptibility axes commonly lie within 20° of the intrusion plane (Tables 1 and 2). k_1 (or k_2, in I_3 fabrics) is a reliable flow proxy in 50% of all sub-sections. In instances where the intersection between IPL and FPL was used (e.g., t#2 sites, and see d#5-6b in Fig. 6), the flow direction is <30° from the k_1 or k_2 axes. Except for minor local misfits, AMS data are in good agreement with intrusion geometries (i.e., flow directions sub-parallel to intrusion walls) and macro-scale kinematic indicators. 71% of AMS flow directions trend within 35° of the macroscopic indicators. A similar fit was observed between macroscopic and magnetic flow fabrics at Allan Hills (70% of AMS fabrics are within 35°: Airoldi et al., 2012) and intrusive swarms elsewhere (Ardnamurchan, Scotland: Magee et al., 2013), suggesting that magnetic lineations presented in this study correlate to magma flow axes.

6.2.1. General magma flow characteristics

Flow components recorded along the margins of analyzed dike intrusions are variable. Magnetic lineation plunges of dikes at Terra Cotta Mountain and Mt Gran range from 7 to 79° (Fig. 9). Of the 35 dike sub-sections analyzed, 17% of magnetic flow directions plunge ≤20°, 37% plunge 21-45°, and 46% plunge >45°. Similarly, the trends of magnetic lineations are variable, and almost any orientation is represented (Fig. 9). These multiple flow directions are also reflected in the orientations of cusps-and-grooves along the walls of intrusions (Figs. 4 and 10).

6.2.2. Magma flow at Terra Cotta Mountain

AMS directions in the Terra Cotta Mountain region follow the geometrical variations of the dike intrusions. For example, within transgressive dikes (e.g., t#1), shallowly plunging (<25°) flow paths occur along shallow dipping segments (t#1a-1, t#1a-3, t#1a-4), whereas steeper flow paths (>25°) are observed only in the steeper dike segments (intrusion dips >50°) (t#1b). Dikes are characterized by variable magma flow paths (Fig. 9 and 11). This is particularly evident in the thickest dikes (d#3 and d#5), where no specific lateral or vertical flow-modes characterize dike selvages and/or the intrusion interiors. For example, analysis of 12 sub-sections along d#5 reveal magma flow plunges ranging 7-79° (Table 1 and Fig. 11), with both shallowly plunging and sub-vertical flow lineations aligning with the plane of the intrusion. AMS flow trends for d#3 range from 267-336°, with shallow-to-moderate plunges (13-37°) along the south-western margin of the intrusion (d#3-1 and d#3-4). Steeper flow plunges (46°-68°) correspond to the innermost sampling sites (d#3-2a and d#3-3, Table 1 and Fig. 11). Multiple flow directions can also be inferred for all individual intrusions from cusps-and-grooves observed on the walls of dikes. Evidence of composite flow-modes is, however, not always observed in thinner dikes (width <10 m, e.g., d#6), although this may in part be the result of smaller AMS sample sets across some of these intrusions.

AMS flow lineations from the Terra Cotta Mountain summit sill (s#4) exhibit westward trends (268-310°), with sub-horizontal plunges (<10°). These magnetic lineations are sub-parallel to lineations of the macroscopic flow indicators.

6.2.3. Magma flow at Mt Gran

The magnetic fabric at Mt Gran exhibits a general consistency with the overall geometry of the sampled intrusions (i.e., flow sub-parallel to the dike walls). Magma flow in dikes is generally sub-vertical, with 75% of sampled sub-sections exhibiting flow plunges >55°. AMS flow lineations constrained for the 30 m-thick central dike (d#7) define an overall north-trending, sub-vertical (63°-78° plunges) flow, with two shallow (19-34° plunges) anomalous AMS directions at the center and eastern margin of the intrusion (Fig. 12). Due to either isotropic or reverse magnetic fabric, no directional information could be constrained for the large sill at the base of the cliff (s#8), the shallowly dipping sills and transgressive dikes (s#9) on the northeast end of the cliff face, and one dike (d#10).

6.3. Summary

Terra Cotta Mountain and Mt Gran samples are characterized by both prolate and oblate magnetic susceptibility ellipsoids, with normal AMS fabrics adding up to about 20%, and intermediate ones to ~45% of the total data respectively. Isotropic or inverse fabrics were discarded from directional AMS analysis.

Magma Flow directions were inferred from AMS fabrics by applying a geometric approach based on the orientation of the magnetic lineation and/or the magnetic foliation plane relative to each intrusion's plane to the magma flow. Over 70% of the magnetic flow indicators and macroscopic kinematic indicators trend within 35° of each other, and are consistent with intrusion geometries. Multiple magma flow paths are common along individual intrusions, with flow plunges as low as 7° and as steep as 79° (19°-78° at Mt Gran) along the dikes, and flow trends of almost any orientation. Magma flow paths defined for the Terra Cotta Mountain summit sill are consistently sub-horizontal, with westward trends.

7. Discussion

Long-distance magma transport in LIPs is often depicted to occur through the emplacement of giant dikes, 100s of km long and 10s of m thick (Ernst et al., 1995). These dikes are shown to have transported magma >1000 km laterally away from an inferred plume source (e.g., MacKenzie dike swarm, Ernst and Baragar, 1992). The development of sill-dominated magmatic systems within LIPs, however, has been increasingly recognized over the past decade (e.g., Thomson and Hutton, 2004; Cartwright and Hansen, 2006; Magee et al., 2014; Magee et al., 2016). These sill complexes comprise a stacked series of mafic intrusions (e.g., the Golden Valley Sill Complex, Karoo LIP, and sill complexes in the North Atlantic igneous province, see Magee et al., 2016 for a review), contrasting with magma systems conventionally depicted for many extensional rift systems (Wright et al., 2012; e.g., magmatic rift segments of Iceland and East Africa: Muirhead et al., 2015; Urbani et al., 2015). AMS studies addressing magma flow within the intrusive systems of sill-dominated LIPs are rare compared to studies investigating sub-parallel swarms of dikes (e.g., Delcamp et al., 2014; Eriksson et al., 2014 and references therein). Below we discuss magma transport dynamics within dikes and sills of the Ferrar LIP.

7.1. Magma transport at Terra Cotta Mountain

Structural and kinematic observations at Terra Cotta Mountain suggest a sill source underlies the exposed dike network (Muirhead et al., 2012). Although many dikes exhibit a lateral flow component, 34% of sampled sub-sections exhibit sub-vertical magma flow paths (>45°), suggesting that the dike swarm probably transported magma upward from this underlying sill. Many of the dikes of this swarm were locally fed upward from large (>10 m thick) “parent” intrusions. For example, a complex network of dikes is observed branching outward from the top of d#3. Magma flow paths along a 280 m-wide region of d#3 are sub-vertical, suggesting that magma travelled upward into the overlying dikes adjoining the upper contact of the intrusion. The replacement of ortho- and clino-pyroxene by plagioclase moving up-dip, determined petrographically, supports a model of vertical flow through the central region of this intrusion. The intrusions overlying d#3 can be seen merging into the large sill (s#4) that caps Terra Cotta Mountain, and probably fed magma vertically into the base of the intrusion.

We interpret the 42° range in distribution of AMS flow paths defined at s#4b sub-sections as a consequence of multiple injection points at the base of the intrusion. Indeed, Muirhead et al. (2012) document at least forty dikes ascending the stratigraphy, many of which connect to the base of s#4, and our AMS results suggest these dikes fed magma upward into this sill intrusion. From these feeder intrusions, we infer that magma flowed outward along radial paths to produce the observed complex magma flow trajectories.

7.2. Magma transport at Mt Gran

At Mt Gran, AMS flow directions in dikes define a dominantly sub-vertical flow (67% of data). In the 30 m-thick d#7, 60% of AMS flow directions are >60°, despite coarse glomeroporphyritic textures away from dike margins, suggesting extensive late-stage crystal growth under slow cooling rates. Anomalous, shallowly plunging magma flow, constrained from intermediate AMS fabrics (Mg 14-1 and Mg 18-1), reflects a mix of oblate and prolate contributions by magnetic particles to the rock's overall AMS fabric (e.g. Ferré, 2002; Aubourg et al., 2008), as well as local variations (vertically and laterally) of magma flow, perhaps owing to pulsation in magma supply across the intrusion.

7.3. Controls on magma emplacement and fracture dynamics

The number and geometric complexity of the localized intrusive networks dispersed throughout south Victoria Land (e.g., Allan Hills, Coombs Hills, Mt Gran, Terra Cotta Mountain) point to the key role of local magmatic stresses in driving dike formation by host-rock fracturing during the forceful intrusion of sills (Muirhead et al., 2012; Muirhead et al., 2014). Our AMS data suggest that dikes ascended from these larger sill intrusions, diverging along several trajectories, intruding both along the walls of pre-existing intrusions, newly formed fractures, and bedding horizons (Fig. 13). Magma deflection along bedding planes represents the primary control on intrusion propagation by pre-existing structures (Fig. 13; see also Airoldi et al., 2011). Up-dip and along-strike variations in dike attitude in other parts of south Victoria Land (e.g., Allan-Coombs Hills: White et al., 2009; Muirhead et al., 2012) represent the response of intrusions to local deviations in the principal stress directions in an otherwise homogeneous and isotropic stress field (Airoldi et al., 2011; Muirhead et al., 2014). Such stress rotations are shown in previous studies to be provided by rigidity contrasts in the layered propagation medium (Gudmundsson and Brenner, 2004; Kavanagh et al., 2006), stress concentrations and rotations related to sill inflation (Johnson and Pollard, 1973; Malthe-Sørenssen et al., 2004; White et al., 2005), and intermittent magma propagation resulting in fluctuating stress concentrations ahead of crack tips, upon both dike and sill inception (Kavanagh et al., 2015), and later cooling (Chanceaux and Menand, 2014).

Variations in magma flow paths along individual intrusions suggest that magma transport cannot be explained purely though a simple vertical flow model. The variety of dike orientations and flow directions, coupled with evidence of multiple injections, suggests that magma propagated intermittently. Variations between shallowly dipping to vertical flow may represent distinct modes of magma flow occurred through time across a single intrusion. For example, as dikes widened (in some instances to >10 m), variations in magma crystallinity and viscosity between intrusion margins and interiors may have coincided with the development of distinct flow paths and velocities. Alternatively, dominant vertical flow might have changed with time to a lateral one, or vice versa. Temporal variations in magma flow directions could result, for example, from changes in magma buoyancy from crystallization and/or magma degassing, or changes in magnitude or direction of driving pressure resulting from opening of new interconnected dikes/sills. Variable magma flow in Ferrar dikes at Allan Hills were interpreted by Airoldi et al. (2012) as the result of "passive" injection of magma into zones of intense fracturing above inflating sills. In this model, magma pressures generated at the dike-tip are not the primary force driving dike-fracture growth and propagation through the host. Instead, opening of country rock fractures formed during sill-related deformation (e.g., Johnson and Pollard, 1973) creates pressure gradients that draw magma into these highly strained zones. Field relationships throughout the region imply that dike intrusions at Terra Cotta Mountain are underlain by a >200 m-thick sill (Morrison and Reay, 1995; Marsh, 2004) and dike-emplacement orientations were probably controlled by local stress conditions related to the inflation of a large underlying sill, rather than by the far-field tectonic stress state (Muirhead et al., 2012; Muirhead et al., 2014). Consequently, variations in dike attitude and magma flow direction recorded at Terra Cotta Mountain are consistent with the sill-driven model of fracture growth and magma propagation of Airoldi et al. (2012).

7.4. Emplacement of the Ferrar LIP during Gondwana breakup

7.4.1 Magmatic-tectonic environment of the Ferrar LIP

Ferrar magmas were originally proposed to have been emplaced in extensional basins in a back-arc rift setting (e.g., Elliot and Larsen, 1993; Storey, 1995), but structural evidence consistent with a rifting environment is absent across the Transantarctic Mountains. For example, no significant Jurassic-age normal faults or long, colinear dike swarms, like those in Iceland and East Africa (Wright et al., 2012; Muirhead et al., 2015), are observed. The thickness (~2,500 m) and age (Devonian to Jurassic) of the Beacon Supergroup are consistent with subsidence rates of only 0.011-0.014 mm yr^{-1}, which is 1-2 orders of magnitude lower than in active continental rift settings (10^{-1}-10^{0} mm yr^{-1}), even those exhibiting extension rates of only a few mm yr^{-1} (e.g., the Kenya Rift Valley, Birt et al., 1997). Rare observations (n=2) of monoclines by Elliot and Larsen (1993) in Ferrar basalt and tuff layers, originally interpreted as fault-related folds (i.e., Grant and Kattenhorn, 2004), are more likely the result of folding at the termination of sills (Hansen and Cartwright, 2006a; Magee et al., 2014), like that demonstrated at Allan Hills, Mt Fleming and Shapeless Mountain (Grapes et al., 1974; Korsch et al., 1984; Pyne, 1984; Airoldi et al., 2011). Elliot (2013) suggested that the substantial thickness of the Kirkpatrick basalts (up to 230 m) necessitates confining topography resulting from rift-related subsidence. However, sill-driven uplift is also shown to produce significant surface topography, resulting in the formation of basins, 100s of meters deep and 10s of kilometers long, observed above sill complexes in seismic reflection imaging (Trude et al., 2003; Hansen and Cartwright, 2006b). At Shapeless Mountain for instance, the intrusion of Ferrar sills produced differential uplift that, in places, would have produced >200 m-high topography at the surface (Korsch et al., 1984). A distinct absence of Jurassic-age normal faulting, rift basin subsidence, and long sub-parallel dike swarms thus provide compelling evidence that Ferrar LIP emplacement was not accompanied by extensional tectonics and the formation of continental rift basins. This conclusion is further supported by the orientations of >600 Ferrar dikes in south Victoria Land (Muirhead et al., 2014). These dikes show no preferred alignments, consistent with emplacement in an isotropic stress regime. Dike orientations were instead controlled by local magmatic stresses related to the emplacement of sills.

These observations suggest that the East Antarctic Margin was not subjected to significant regional tectonic stresses prior to and during Ferrar LIP emplacement, which may explain why continental breakup did not initiate throughout Antarctica during and after

Ferrar-Karoo magmatism. Instead, breakup of the Gondwana supercontinent focused in what is now the Weddell Sea region.

7.4.2 Broad-scale emplacement of the Ferrar LIP

Igneous rocks of the Ferrar LIP crop out in present day Antarctica, SE Australia, and New Zealand. Although the Ferrar magmatic province exhibits a broad geographic distribution, the remarkably homogenous compositions exhibited by Ferrar rocks suggest a single source (Elliot et al., 1999). Furthermore, decreasing Mg# and MgO contents away from the inferred source area (Weddell Sea) along the length of the province are consistent with fractional crystallization during lateral magma flow (Elliot and Fleming, 2000; Leat, 2008). Widespread Ordovician dikes of the Vanda dike swarm have been mapped in basement granitoids and meta-sedimentary rocks (Allibone et al., 1993), yet no Ferrar dikes, or sills, are observed at basement depths, below the Basement Sill, ~500 m from the lower contact of the Beacon Supergroup (Marsh, 2004; Leat, 2008). As suggested by Leat (2008), these observations imply that long-distance, lateral magma transport in the Ferrar LIP occurred almost exclusively in the Beacon Supergroup (Fig. 14).

AMS flow directions from dike swarms presented in this study, as well as those at Allan Hills (Airoldi et al., 2012), provide insights into regional trends in magma flow in dikes across arguably the best-exposed portion of the province in south Victoria Land (Fig. 14). These results show no consistent lateral or vertical flow components that typically characterize the dike feeder systems of LIPs (Ernst and Baragar, 1992). It is therefore likely that the observed Ferrar dikes were not responsible for the regional transport of magma laterally along the East Antarctic margin during Ferrar magmatism. Instead, magma flow in dikes was of local importance, creating pathways through which magma could ascend the stratigraphy through interconnected sills and, eventually, erupt at the surface (Muirhead et al., 2014).

As Ferrar dikes were not responsible for long distance magma transport along the province, we highlight the Ferrar sills as the probable conduits throughout which magma was transported laterally ~3,500 km within Beacon Supergroup rocks across the Gondwana supercontinent from its source (see conceptual model in Fig. 14). Lateral magma transport in sills for ~3,500 km would require both sufficient magma input and appropriate thermal conditions to avoid solidification and arrest (Annen and Sparks, 2002; Chanceaux and Menand, 2014). One of the main limiting factors to long-distance transport relates to the original magma temperature and the temperature at which magma freezes and stalls (solidification temperature). However, magma intrusions and lavas flows in LIPs are shown to travel >1,000 km with assistance of shear heating (i.e., viscous dissipation) (Fialko and Rubin, 1999) and the insulating effects of a fine-grained chilled intrusive margin (e.g., Delaney and Pollard, 1982; Marsh, 2002), or an external crust (Keszthelyi and Self, 1998). In many ways, sills are similar to lava flows, as they form through the progressive lateral propagation, inflation and linkage of magma fingers or lobes (Pollard et al., 1975; Thomson and Hutton, 2004; Schofield et al., 2010; Schofield et al., 2012), some of which reach thicknesses of 10 to 100s of meters (Hansen and Cartwright, 2006a; Schofield et al., 2015). Although magma propagation speeds for upper crustal basaltic intrusions (e.g., 10^{-1} to 10^{-2} m s^{-1}; Wright et al., 2012) are lower than for basalt lavas (101 to 10^{-1} m s^{-1}; e.g. Keszthelyi and Self, 1998; Self et al., 1998; Self et al., 2008), intrusions are comparatively more insulated because they are surrounded by warmer crustal rocks rather than cool atmosphere.

The shallow plumbing system of Antarctica comprises a series of stacked, interconnected sills. The four major sills in south Victoria Land average ~300 m in thickness (Marsh, 2004; Elliot and Fleming, 2008). By applying a heat balance model similar to that developed by Keszthelyi and Self (1998) for lava flows with an insulating crust, the thermal efficiency of sill flow is determined by viscous heating, conductive heat loss from the upper and lower margins of the intrusion, and thermo-physical parameters. Assuming conservative magma propagation velocities of 0.03, 0.05 and 0.1 m s^{-1}, negating the effects of viscous heating, and applying typical thermo-physical properties for mafic magmas (injection temperature of 1,250 °C, density 2,700 kg m^{-3}, thermal conductivity of 2.1 J s^{-1} m^{-1} °C, specific heat of 1,200 J kg^{-1} °C; Barker et al., 1998; Wohletz et al., 1999; Wang et al., 2010), we estimate that the maximum heat loss for a 300 m-thick Ferrar sill emplaced at 2.5 km depth would be between 0.04 and 0.01 °C km^{-1} (refer to Section 2 of the supplementary material). These thermal constraints would have affected transport of magma in 300 m-thick Ferrar sills for 3,500 to 12,000 km along the East Antarctic margin before solidifying.

The thermal constraints on long-distance magma transport in Ferrar LIP sills may be tested further by estimating the minimum sill thickness required for sustained magma flow (cf. Holness and Humphreys, 2003, and refer to Section 2 of the supplementary text). Adopting the thermo-mechanical intrusion parameters of Holness and Humphreys (2003), and assuming a constant and conservative overpressure at the magma source equal to the tensile strength of rock (3 MPa; Schultz, 1995), we estimate that lateral magma transport for 3,500 km across the East Antarctic Margin would require a minimum sill thickness of 110 m. Long-distance magma flow would be further assisted by the channeling of Ferrar sills within the Beacon Supergroup sedimentary basin (Leat, 2008), which is laterally continuous along the full length of the East Antarctic margin (Barrett, 1981). These estimates are similar to those obtained for some of the longest identified Deccan lava flows (Rajahmundry lavas: Self et al., 2008), which advanced >1,000 km in a cooler subaerial environment, and are consistent with field studies and thermo-mechanical models of long-distance transport in giant dikes, which in some instances extend for 1000s of km laterally from their source (e.g., the MacKenzie dike swarm: Ernst and Baragar, 1992; Fialko and Rubin, 1999).

8. Conclusions

Magma flow in dike swarms of the Ferrar LIP investigated in this study contrast with flow paths predicted by classic models of dike transport in LIPs and magmatic rift settings (Ernst and Baragar, 1992; Wright et al., 2012). Our data suggest that dikes transported magma vertically between sills rather than controlling long-distance lateral transport in sub-parallel swarms throughout SVL.

AMS data provide new insights into the growth of sill-fed dike swarms in LIPs. The heterogeneity of magma flow and variability in dike attitudes at various depths and scales (from a few meters to kilometers) suggest that tectonic stresses had little influence on the growth of the intrusive networks. A complex flow model, with both shallowly dipping and sub-vertical flow components, can be defined for most intrusions. Variable magma flow within individual intrusions may have developed along strike and up-dip either during a single intrusive event, and/or as a result of multiple injections, and locally represent early- *vs* late-stage magma propagation.

The Ferrar LIP formed during the earliest stages of Gondwanaland breakup and was originally interpreted to be emplaced in a back-arc extensional setting. However, fracture systems trends, dike patterns, and magma flow patterns in SVL are consistent with magma emplacement in an isotropic stress regime, with bedding anisotropy providing the dominant structural control on intrusion geometries. Flow patterns observed regionally in dike swarms across south Victoria Land show no consistent lateral or vertical flow directions. As Ferrar dikes were not responsible for the long-distance transport of magma laterally across Antarctica, the Ferrar sills remain the most likely candidate for long-distance transport.